



## **Pathways to Carbon Neutral Industrial Sectors: Integrated Modelling Approach with High Level of Detail for End-use Processes**

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# Pathways to Carbon Neutral Industrial Sectors: Integrated Modelling Approach with High Level of Detail for End-use Processes

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## ABSTRACT

Industry constitutes a substantial share of the energy and fuel consumption in energy systems. Types and patterns of usage within different industrial sectors are diverse. In this paper, we illustrate the energy and fuel use in Danish industry by 24 end-uses and 20 fuels and provide hourly profiles for electricity, space and process heating. The heat profiles are based on measured natural gas consumption. While seasonal patterns are predominant for space heating, process heating and electricity consumption are found to follow sector-related activities on a temporal scale. Building on this data analysis and profile generation we describe an approach to implement this level of detail in an integrated energy system model. This work is part of assessing the role of industry in the future Danish energy system.

## KEYWORDS

Industry energy use, hourly consumption, demand profiles, electricity, space heating, process heat, energy system model.

## INTRODUCTION

In light of the recent international Paris Agreement, the necessity to aim at carbon neutral societies and thus switch to 100% renewable energy systems is a clear goal. When striving for completely renewable-based energy systems, a cross-sectoral modelling approach with a high level of detail is necessary [1]. The industrial sector constitutes an essential part of the energy and fuel use in an energy system. In Denmark, industry and agriculture accounted for 20% and services for 13% out of a total final energy consumption of 587 PJ in 2014 [2]. In the same year, on a European scale, industry and agriculture consumed 28% and services 13% of the total energy demand [3].

Specific characteristics make the industry sector exclusive compared to others. Among the most relevant are:

- fuel usage as feedstock
- process and excess heat on a wide range of temperature levels
- a high variety of demand elasticity
- self-production of heat/electricity by industry entities
- a high variety of heat and electricity profiles
- geographical location (decisive for possibilities of district heating supply and potential usage of excess heat).

Analyses regarding energy usage in the industry sector have to take these characteristics into account.

Relevant and fundamental changes are to be expected in the industry sector to reduce greenhouse gas emissions. For example, electrification of many industrial processes is discussed on European scale as an important measure for reducing carbon emissions [4]. Moreover, high temperature heat pumps for process heat and integration of high temperature heat from electrolysis is discussed for a Danish energy concept [5]. Other measures include increased efficiencies of industrial processes [6] and the possible usage of excess heat from industrial processes [7]. Furthermore, with an increasing share of generation of renewable gases in Denmark, these have the potential to replace natural gas to some extent [8–10]. The foundation for a realistic quantification of the potential for those emission reduction options (energy savings, electrification and fuel replacement) is a clear fuel-input separation for different end-uses in the industry sectors.

To assess the impact of changes in industrial energy usage on the energy system and its transition to renewable sources, an energy system view is indispensable. With increasing shares of fluctuating electricity sources, the challenge is to understand how to maintain security of supply and stability for the system at every hour when such changes are implemented [11]. Temporal patterns (namely hourly profiles) of energy demand and supply are therefore fundamental for that particular task.

The aim of the paper is to define methods to model industry in high level of detail within an integrated energy system. The methods are applied on a Danish case study, including specific data on fuel usage for each of the industrial end-use processes. The study contributes with three main objectives: 1) explain in detail how energy use (in terms of heat, electricity and fuels) is distributed among the end-uses' industrial energy processes; 2) develop hourly profiles for heat and electricity consumption for the processes within the industry; 3) provide a method to integrate the findings in a sector integrated energy system model and propose additional analysis that can be performed with this extension.

## ENERGY IN DANISH INDUSTRY

### Danish industry structure

The term industry is differently defined in literature and statistics. In this paper, industry refers to and includes agriculture, manufacturing and services.

The Danish national version of EU's nomenclature (NACE) is the Dansk Branchekode DB07 (Danish Branch Code). It is a statistical classification of economic activities, classifying each enterprise based on its main activity [12]. Out of 127 groups of economic activities, detailed data on energy usage are available for 57 [13]. Each of these sectors include sector-related activities. The allocation of such activities is commonly acknowledged, but might differ for different study cases. In this study, the allocation of economic activities to the sectors differs slightly from the DB07 classification. The exact allocation can be found in the Annex of [13]. The above mentioned 57 sectors do not include refinery, public service and construction, hence these sectors are not included in this study.

The analysis thus focuses on 57 sectors, where the consumption is disaggregated in a total of 24 processes (i.e. end-uses) supplied by 20 types of fuels (based on data from [13]). The industrial sectors are categorized in five main groups according to similarities in temporal patterns of energy consumption. This categorization allows 1) an easier comparison of the electricity and heat demand profiles within the same group (e.g. differences and similarities) and 2) to investigate the yearly pattern of such groups. The categorization, as well as underlying assumptions, are based on [14]. The categories applied in the study are: agriculture, production single shift, production double shift, production triple shift and services. They will be described in the following and thereafter checked and tested against real data.

*Categories description.* In **agriculture** the energy consumption follows a seasonal pattern linked to seasonal dependent activities. The consumption is lower during summer and higher during

fall and winter. Throughout the year, the consumption is higher during the day (working hours from 6 to 18) and week days and lower by night and in the weekend. Fuel use is mostly related to the equipment employed for the activities and for heating of the production units (e.g. stables and greenhouses). The use of fuels is linked to the daily activities, but can happen also out of working hours due to lightning, ventilation and other auxiliaries.

The **production** group includes the sectors concerning manufacturing and extraction. The subdivision in single, double and triple shift is linked to the weekly activities. *Single shift* facilities typically operate during normal working hours in the week days and are closed during weekends and holidays. *Double shift* facilities have longer operating hours (about 15 hours a day), they close during the night and often during weekends and holidays. *Triple shift* facilities run as continuous production (i.e. almost constant consumption throughout the year) and close down only few times a year (e.g. for holidays). Typically, the energy consumption of production facilities is high during operation and relatively low when the production is closed down. Nonetheless there is often a steady baseload consumption for processes such as auxiliaries or ovens. The energy consumption of the production sectors is mixed between various fuel types, heat and electricity.

The **service** group includes activities that are mostly conducted during normal working hours. The energy consumption is high during daytime and weekdays, and lower during the nights and in the weekend. Some exceptions to this "schedule" can occur. The activities vary over the year, with some operating mainly outside holidays and others mainly during holidays. As an aggregated sector the total energy consumption is mostly constant over the year, besides energy for space heating purposes. In terms of energy consumption, this group mainly uses oil products, district heating and electricity.

*Fuels and end-uses.* The energy end-uses are classified according to 24 processes. They can be grouped in five main end-uses: *internal conversion losses*, *process heating* (heating/boiling, drying, inspissation, distillation, burning/sintering, melting/casting, other process heating up to/over 150°C), *transport* (moving machinery, transport), *space heating* and *utilities* (energy for heat pumps, lightning, pumping, comfort cooling, cooling/freezing, comfort ventilation, blowers, compressed air, hydraulic machinery, other electric motors, IT and electronics, other electric consumption).

The fuel supplied for the processes includes coal, fuel oil, petroleum coke, coke, diesel, gasoline (unleaded and coloured), LPG, natural gas, gas-oil, bio-gas, biomass (wood chips, wood pellets and straw), bio-oil, waste, electricity, district heating, solar heating and heat pumps.

## Energy use in sectoral end-use processes

The energy usage in industry by process and by fuel is described and illustrated in the following. The analysis is based on data from [13] for Denmark in 2012 and includes all energy and fuel usage including use for transport.

Figure 1 illustrates the final energy usage by type of fuel according to the five main categories: agriculture, production single, double, triple and service. In total, the sectors' energy use accounts for almost 200 PJ with production (excluding refinery and construction) accounting for 93 PJ, service (excluding public service) for 69 PJ and agriculture for 37 PJ. Double and triple shift groups show a significant higher share of energy consumption compared to the single shift group.

Agriculture and service are characterized by a great use of fossil oil (gasoline, kerosene, diesel, LPG). Natural gas is predominant in production and solid fossil fuels (petroleum coke, coal, coke) mainly in triple shift production. Renewable solid fuels have a visible share in part of the production sector (single, double) in the form of wood and in agriculture in terms of straw. In the year the data originates from (2012), roughly 0.1 % of the energy used in industry is based on biogas. District heating provides a significant share of energy in the service sector but plays a minor role in agriculture and production. Electricity is utilized in all sectors with the service

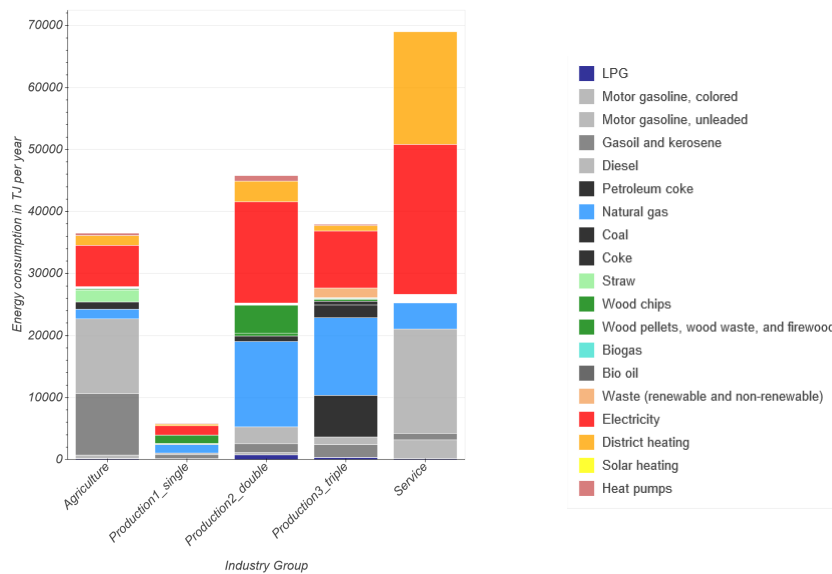


Figure 1. Final energy use in different Danish industry groups by fuel (based on data from [13])

sector being the largest consumer - one third of the service group's energy consumption. Figure 2, Figure 3 and Figure 4 illustrate in detail, as heat maps, the use of energy in different industrial energy processes for the year 2012. The production group is aggregated for visual purpose. The darker the colour, the higher the usage of that particular fuel in the end-use process.

The legend on the right shows the relation of the colours to the absolute values in TJ; note also that the scale between the three figures differs. The x-axis indicates the fuels. The y-axis shows the end-uses in detail ordered according to their aggregation: Internal Conversion Losses, Process Heating, Space Heating, Transport and Utilities.

For all the groups the electric applications blowers, comfort cooling and ventilation, compressed air, freezing, heat pumps, hydraulic machinery, IT and electronics, lightning and pumping use electricity as main source, with lightning and electric motors being the most intensive consumers.

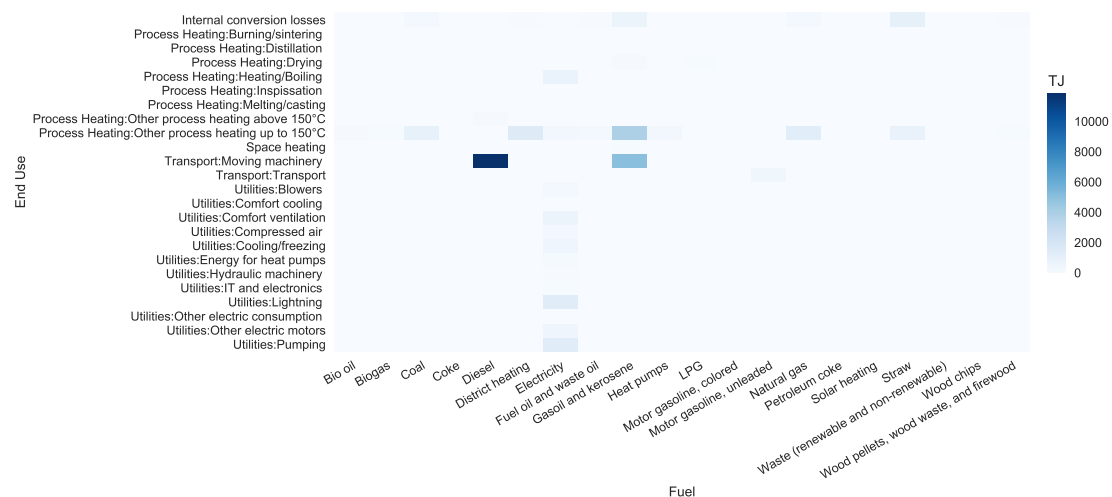


Figure 2. Energy usage in Danish agriculture by end-use and fuel. Based on data from [13]

In *agriculture*, the most used fuels are diesel, electricity and gasoil and kerosene. Moving

machinery and process heating dominates the energy consumption. Diesel, gasoil and kerosene are mainly used for moving machinery. Fuels for process heating are slightly more diversified: district heating, natural gas, straw and coal, electricity and heat pumps following gasoil and kerosene. The major end-use in processes is heating up to 150°C. Electricity is used for different utilities; lighting and pumping are the biggest consumers.

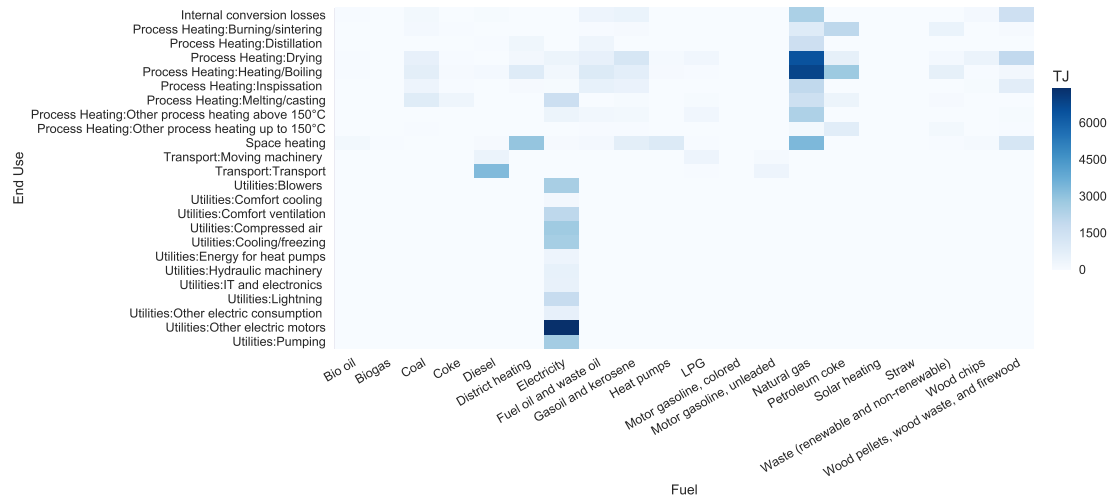


Figure 3. Energy usage in Danish production by end-use and fuel. Based on data from [13]

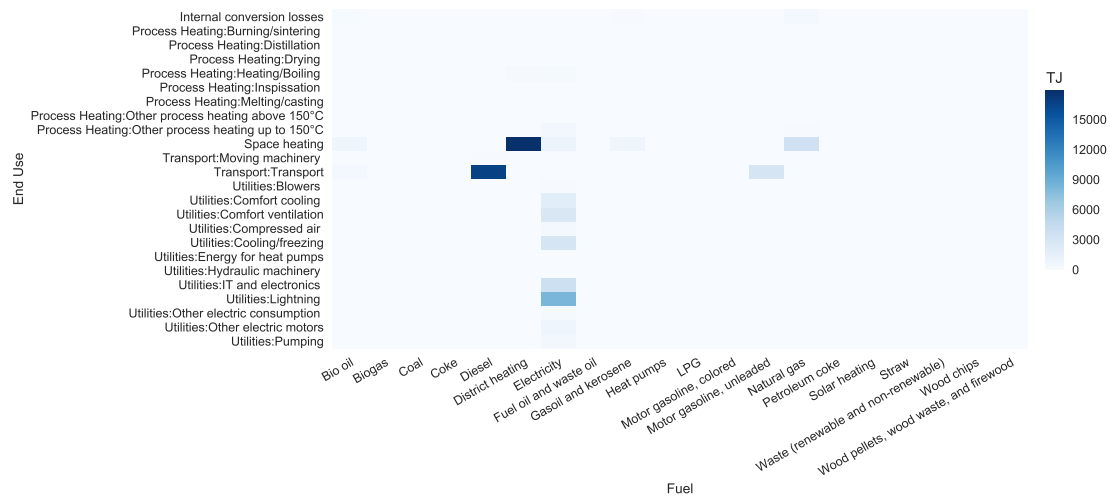


Figure 4. Energy usage in Danish service by end-use and fuel. Based on data from [13]

In the *production* group, natural gas, electricity, fuel oil, gasoil and wood are the most employed fuels for a wide variety of end-uses. Natural gases cover the highest share for process heating. However, also petroleum coke, wood, coal, gasoil, kerosene and fuel oil constitute a relevant part of the consumption.

In *services*, space heating, transport and lightning dominate the energy consumption. The most employed energy carriers are diesel, district heating and electricity. Heat is mainly provided by district heating, followed by natural gas, bio oil, electricity, gasoil and kerosene. Transport also constitutes a high share of energy usage mainly provided by diesel and gasoline. Electricity is used for processes like lighting, IT and electronics, cooling/freezing, as well as comfort cooling and ventilation.

Figure 2, Figure 3 and Figure 4 show that natural gas plays an important role for process heating in the production group. Nonetheless, the use of a multitude of other fuels for different processes is also relevant. The variety and diversity of end-uses and fuels provides a preliminary indication of the industrial potential for savings, electrification and fuel replacement. Based on this detailed data, it is possible to flexibly cluster by type of fuel or type of process depending on which input format is required for analysis in energy models.

In the following section, we concentrate on consumption profiles for fuel consumption for heat purposes and electricity, excluding the energy use for transport.

## ENERGY CONSUMPTION PROFILES

### Methodology

The hourly resolution of energy demand and supply provides specific details about the flexible operation of energy generating technologies, transmission and use of energy. In energy systems with high shares of fluctuating renewables, electricity and heat demand have essential influence on the system operation and configuration. Since hourly energy consumption profiles are fundamental in an energy system model with an hourly temporal resolution, such energy consumption profiles have to reflect realistic patterns.

*Electricity.* Electricity consumption profiles are often openly available only at a higher level of aggregation. The Danish transmission system operator Energinet.dk [15] and Nord Pool, the Nordic power market trading platform, provide such data on an hourly resolution at country and regional level [16]. Based on those and other data sources [17], Andersen [18, 19] developed a methodology to generate industry-sector related electricity consumption profiles (percentage load profiles). This data covers approximately more than half of the electricity consumption profiles of the 57 industrial sectors considered and are utilized in this study. These profiles are grouped according to the main five categories (agriculture, service, production single, double, triple) to enable an easier comparison on consumption patterns in the same group. The consumption profiles for the remaining sectors (i.e. the ones without a profile) are then derived through three steps:

1. given a sector (e.g. gardening) with a missing profile, we first check to which main category it belongs (in this case agriculture);
2. the selected sector is then compared to the characteristics of the other sectors (for which profiles are available) in the same category in terms of: fuel consumption, end-uses and qualitative characteristics about the pattern (e.g. seasonal trends);
3. the profile of the missing sector is set to be the same as the profile, in the same category, which share similar characteristics.

The process allows to estimate consumption patterns for all the 57 sectors. The relative profiles are then associated with the absolute value of consumption to determine the hourly load profiles in absolute values (MWh). The resulting electricity profiles are thereafter checked in the result section.

*Heat.* Industrial heat load profiles differ from electricity demand patterns. In industry, heat is primarily used for two purposes: *space* and *process heating*. The former considers heating of working environment, the latter is generally related with higher temperature heat generated using fuels that serve as primary source for the industrial processes (e.g. melting of metals). Due to the nature of the end-purposes, it is expected that the heat profiles follow different patterns. Space heating should show a clear seasonal pattern linked with the outdoor temperature. On the other hand, the consumption pattern for process heat is expected to vary according to the type and operation of end-use processes considered as well as on the work-pattern.

As natural gas was found to be the most-used fuel for heat-related processes in industry (Figure 3), we assume that the consumption profile of natural gas represents the patterns of process heat demand in industry. The same is considered for space heating, since district heating and natural gas are also comparable in order of magnitude. Hourly gas delivery data, for the year 2016, for approximately one third of Danish customers are used [20]. The gas consumption data, available at end-use level for each company, are separated between space and process heating purposes. The hourly data of gas consumption can be related to the industry sectors by the DB07 Danish branch code. The samples are aggregated to create two load profiles (space and process heat) for each of the 57 sectors, within each of the main categories. Since the number of measurements varies for each company and the number of companies varies for every sector, both the space and process heat profiles represent an average among the company's end-uses and among the companies in the same sectors. Although this arrangement implies a lower data resolution, it gives a fair representation of the average fuel consumption pattern for the sectors considered. For the exceptional cases in which profiles were missing, a method similar to the one used for the electricity was adopted. As the use of natural gas is not that common in agriculture (see Figure 2), no profiles were generated for the industry sectors in the agriculture group.

## Results

**Electricity.** The resulting electricity consumption profiles are presented in absolute (MWh) and relative values (%). The relative profiles represent the share of fuel usage in one hour in relation to the yearly consumptions. The resulting profiles for each of the 57 sectors are, for verification reasons, grouped according to the five groups. For each group an average profile is generated. Figure 5a reports a summary of the resulting profiles' variation. The results are presented as boxplots, a useful tool that provides an easier visualization of the results. The extent of the line represents the range of values. The main coloured box identifies where 25%, 50% and 75% of the values lie (respectively the lower border, middle line and the upper border). Outlying extreme values are shown outside the upper-most horizontal line.

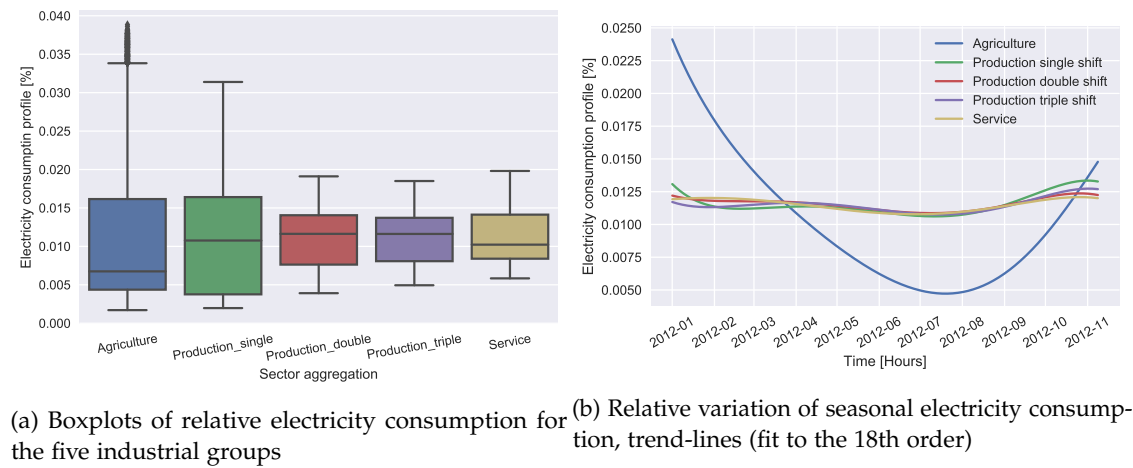


Figure 5. Description of electricity consumption profiles (y-axis different for the two graphs)

The biggest range of variations within the profiles occurs for agriculture and production single shift. This is in line with the underlying assumption that agriculture has a seasonal profile related to the activities while production single shift varies between weekdays, weekends and holidays. For production, the reader can observe that the size of the boxplots (representing the variation) gets smaller for higher number of production shifts (i.e. the triple shift shows the smallest box). A lower range of variation in the profile confirms that the consumption is rather constant throughout the year.



Similar conclusions can be drawn analyzing the trend-lines of the yearly consumption profiles for the five sectors. Figure 5b shows that agriculture presents a greater seasonal variation when compared to other sectors. Service, production single and double shift show a decrease in consumption in correspondence with holidays (summer holidays in July). On illustrations with a higher resolution (not shown in this paper), it can be seen that production triple shift has a more constant profile during the year, compared to double and single shift.

Figure 6 shows that the absolute profiles of the singular sectors within each aggregated group vary in size because of the different amount of energy consumption. Concerning the pattern, they generally follow same weekly profile but differ in the spread between highest and lowest demand. Figure 6a provides an example for the production double shift group. Compared to the average (blue thick line) the magnitude of electricity consumption varies among the different sectors but still follows the trend of the average. Some exceptions still occur (e.g. small peaks out of weekdays working hours and slightly higher consumption during the weekend) but they are in line with the characteristics of the production double shift group.

Figure 6b shows the contribution of the industry to the total electricity demand in Denmark. For the selected sample week, the industrial electricity consumption represents around half (50%) of the total electricity consumption.

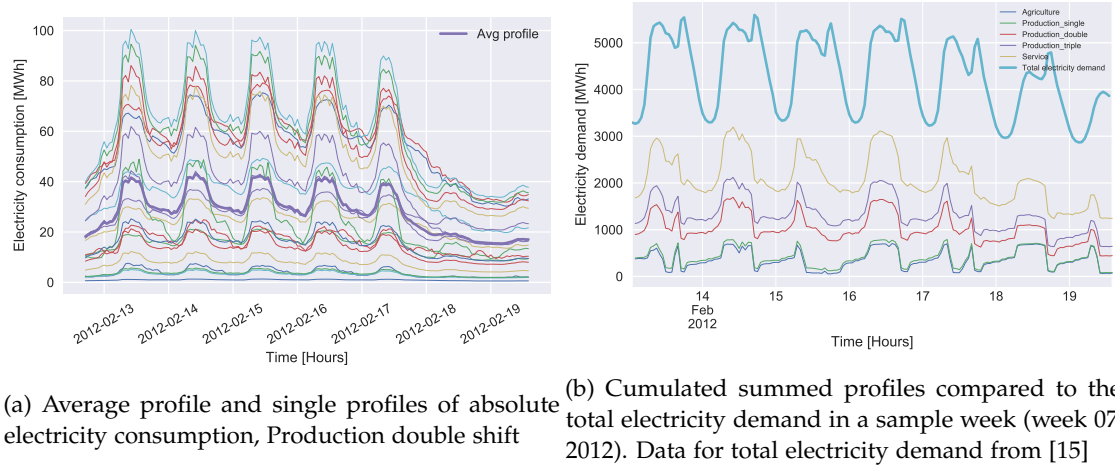


Figure 6. Electricity consumption profiles

Heat. This section presents the findings for the fuel consumption profiles for space and process heating purposes. The newly created relative profiles are analysed by boxplots, presented in Figure 7. Similar to the electricity profiles, the reader can observe that the size of the boxplots, and thus the variation of the profile, decreases with the increasing number of shifts. This indicates that triple shift consumption profiles are relatively more stable throughout the year. The boxplots for space and process heating also show, as expected, that most outliers are to be found in process heating rather than space heating.

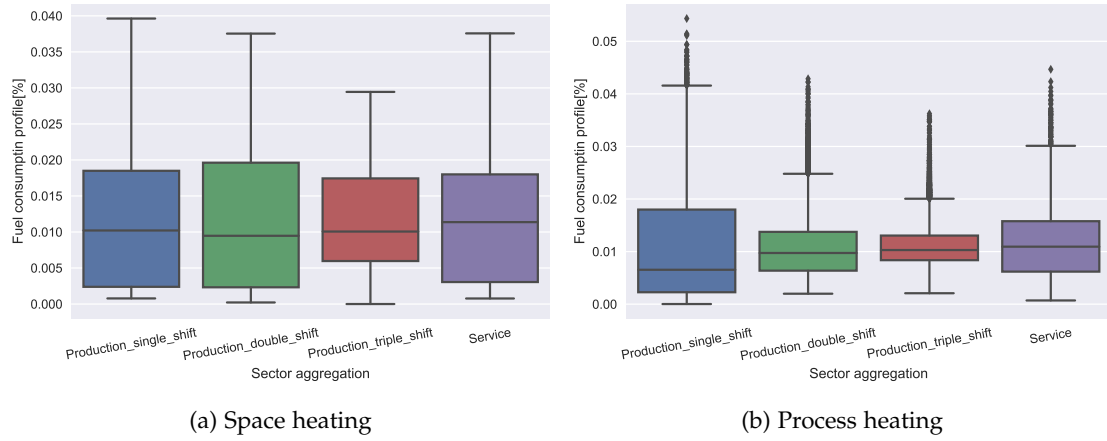


Figure 7. Boxplots of relative fuel consumption profiles

Figure 8 and Figure 9 present the seasonal variation in fuel consumption for space and process heating on a yearly and weekly scale in relative values. On a yearly scale, the fuel consumption for *space heating* (Figure 8a) shows a temperature-related trend, with higher consumption in fall and winter, and a lower consumption during summer and spring. On the contrary, consumption for *processes heating* (Figure 9a) shows a more stable profile, not related with the season. In the same figure, the sudden decrease in energy consumption during March-April, July-August and December is related with the closure of activities during holidays (Easter, summer and Christmas respectively).

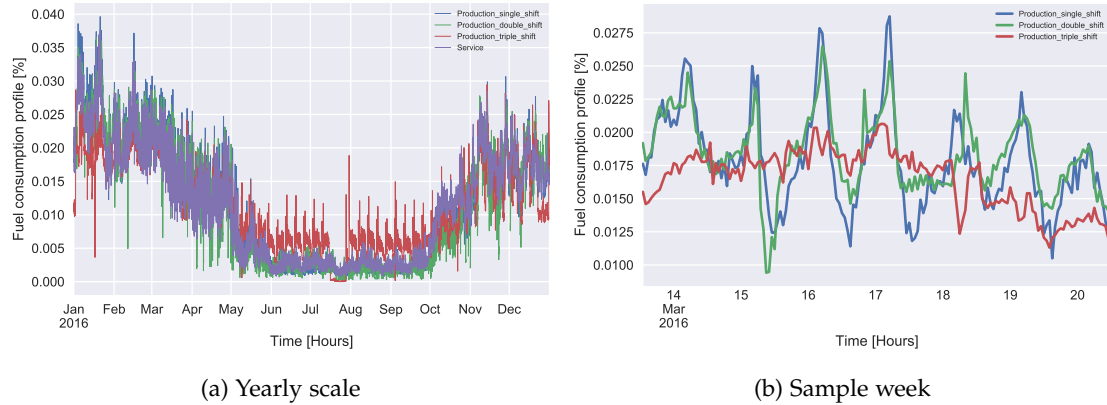


Figure 8. Space heating, seasonal variation of heat consumption profiles

On a weekly scale, the development of the profiles shows diverse trends. For *space heating* (Figure 8b), the weekly profile is rather stable within the days, with variations related only with day/night activities (i.e. every day the consumption grows in the morning, reaches two peak within the day and then decreases by night). On the other hand, the fuel consumption profile for *process heat* (Figure 9b) present day-related particularities: the energy consumption is higher during the weekdays and lower during the weekends. This is different for the triple-shift profiles which have a rather constant profile throughout the entire week for both for space and process heat.

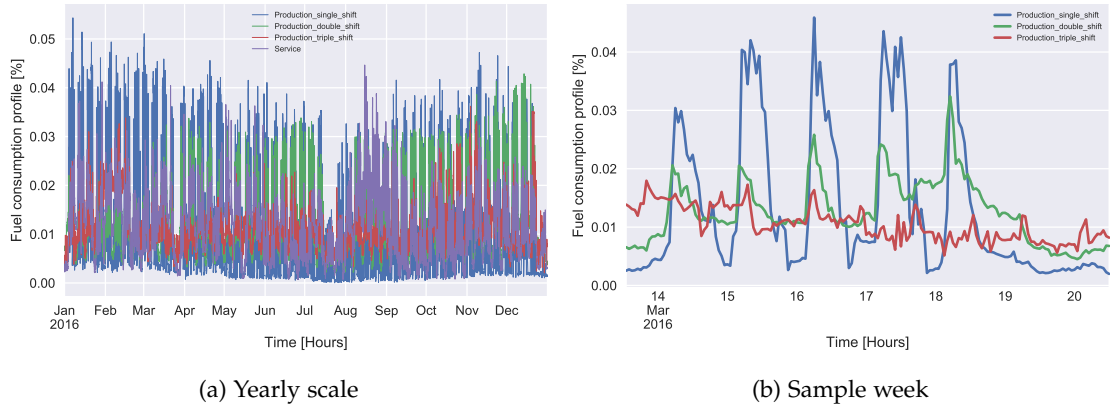


Figure 9. Process heating, seasonal variation of heat consumption profiles

The reader can also notice the different timing of fuel consumption during the week (Figure 8b and Figure 9b). Production single shift activities operate mainly during day hours and close by night and weekends while production double shift present a slightly flatter profile, implying longer working hours.

Figure 10 shows the average profile vs. the singular profiles for processes in production single shift in absolute values of fuel consumption ( $m^3$  natural gas). Focusing on the hourly development during the selected week, the single profiles (thin lines) differ among each other in order of magnitude and pattern. The average profile (thick green line) provides an easier understanding of the general hourly consumption's trend. Summarizing, hourly consumption profiles for electricity, space and process heat have been set up and analyzed facilitating integrated modelling.

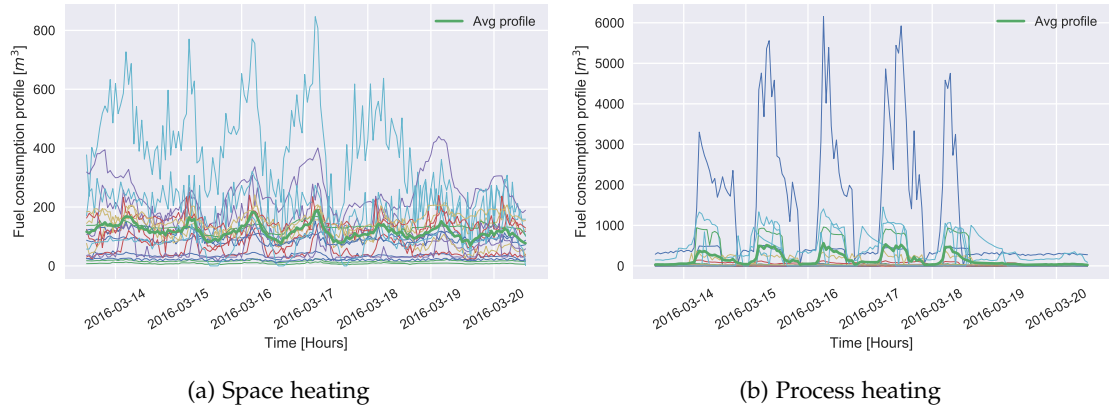


Figure 10. Weekly variation of absolute heat consumption profiles, sample week for production single shift sector.

## INDUSTRY IN AN INTEGRATED ENERGY SYSTEM MODEL

### Type of model

The energy system perspective enables to assess the role of industry in achieving pathways to low or zero carbon energy systems. As the interrelations between the electricity and the heating sectors are increasing (e.g. due to the use of heat pumps), only a concurrent consideration can reflect the cost-minimal solutions from a system perspective. Furthermore, a high temporal resolution is required for assessing the flexibility necessary in a system with high shares of fluctuating energy. The open source energy system model Balmorel covers the necessary

conditions. The model considers the electricity and district heating demand with a possible hourly resolution. It allows an optimization of operation and investments and a flexible division of areas. The original version is described in [21] and the model is openly available [22]. It has been applied for a wide range of studies, such as integration of renewable technologies in the energy mix, analysis of market conditions, policies implementation, future role of district heating and impact of energy efficiency technologies in the energy system [23–28]. Balmorel will be used for modelling industry in the integrated Danish energy system. For this purpose, the model will be extended with respect to the level of detail of energy demand and end-use processes in industry (excluding transport).

## Energy system model extension

Figure 11 shows the original structure of the Balmorel model at regional level. For a certain region considered, the energy demand (electricity and heat) is considered as a "block of energy" that includes the demand of all the sectors (industry among others). Consumption profiles are defined for electricity and heat on an aggregated level (i.e. as total regional electricity and areal heat demand).

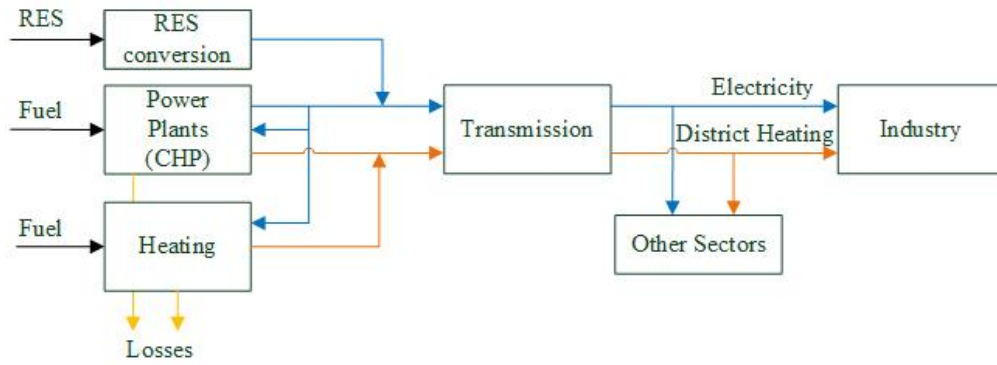


Figure 11. Current representation of industry in the energy system model (Adapted from [6])

Figure 12 shows the novel structure proposed, with focus on industry. Electricity, heat and fuels are considered as energy inputs for the end-use processes in industry. Fuels can also be used as fuel-feedstock directly for the industrial processes in the model to better represent reality. Heat is separated as space and process heat and distinguished between different temperature levels. In this way, it can be supplied by different sources and technologies. Specific electricity profiles for the industrial sectors are the basis for the demand profiles fed into the model. Space heating for the industry sector can be supplied by district heating, but can also be self-generated, using the fuel in a plant on site to generate electricity and heat.

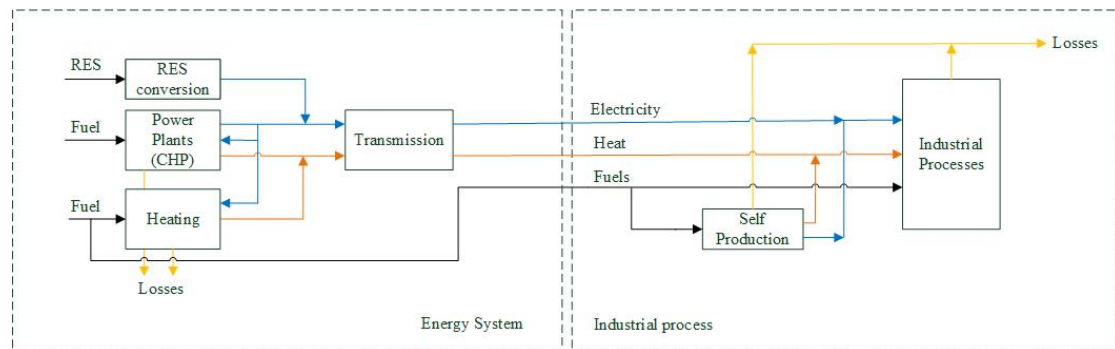


Figure 12. Extended representation of industry in the energy system model (Adapted from [6])

## CONCLUSION

The analysis of energy use and consumption profiles has highlighted particularities of the industry sector. While electricity and natural gas are found to be the predominant energy carriers, other miscellaneous fuels have also a relevant role in the energy use among all the sectors.

The analysis of the consumption profiles showed the diversity (in terms of magnitude and pattern) between the different sectors, for space, process heat and electricity. For identifying temporal patterns of energy utilization in industry, clustering the industrial sectors in the groups agriculture, service, production single, double and triple shift according to similarities in energy consumption, have proven to be useful. Seasonal patterns were identified for space heating related fuel consumption. The profiles of fuel demand for process purposes and electricity consumption were found to follow sector-related activities on a temporal scale.

Such a meticulous investigation on fuel consumption for various end-uses in different sectors facilitates analyses about fuel substitution, electrification and savings. The presented data analysis and the proposed model refinement enables analysis that would not be possible on an aggregated level, as it is at the current state. Energy system models can thus benefit from this deep level of particulars when performing analysis on the impact of changes, in the industrial sector, on the energy system. The main benefit of representing the hourly consumption of sectors is the ability to assess the implications of fuel substitution, savings and flexible consumption.

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